DELAY/DISRUPTION TOLERANT NETWORKING

Evaluation of Opportunistic Contact Graph Routing in Random Mobility Environments

Section 332 – Communications Research and Architectures

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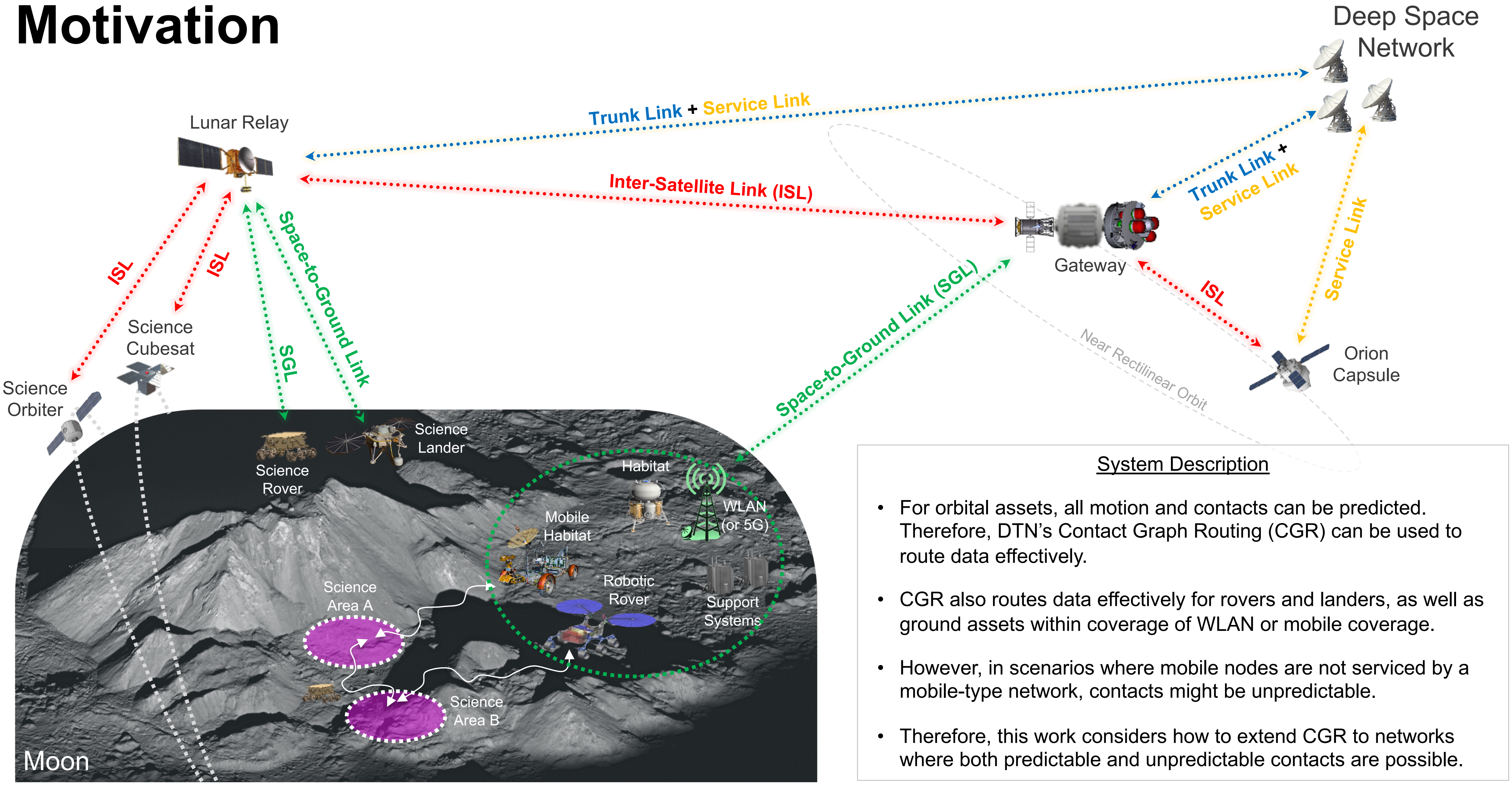
Motivation



Scenario adapted from the IOAG Lunar Communications Architecture Working Group

System Description

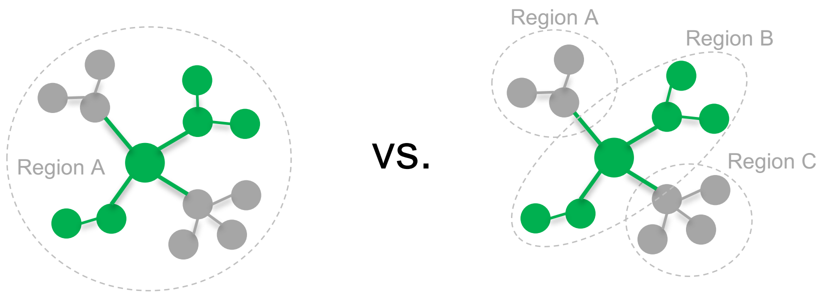
- For orbital assets, all motion and contacts can be predicted. Therefore, DTN's Contact Graph Routing (CGR) can be used to route data effectively.
- CGR also routes data effectively for rovers and landers, as well as ground assets within coverage of WLAN or mobile coverage.
- However, in scenarios where mobile nodes are not serviced by a mobile-type network, contacts might be unpredictable.
- Therefore, this work considers how to extend CGR to networks where both predictable and unpredictable contacts are possible.

Problem Statement

- **GOAL**: Extend DTN routing capabilities to networks with both predictable and unpredictable contacts to enable seamless end-to-end routing.

- To answer this research question, we have to answer:

  1. Architectural Decision: Define single region and enhance CGR capabilities vs. Define regions with different specialized routing protocols.



- Simple
- Interoperable by definition
- Can we do it?

- Increased complexity
- Interoperability is not a given
- Do we get better routing?

Legend

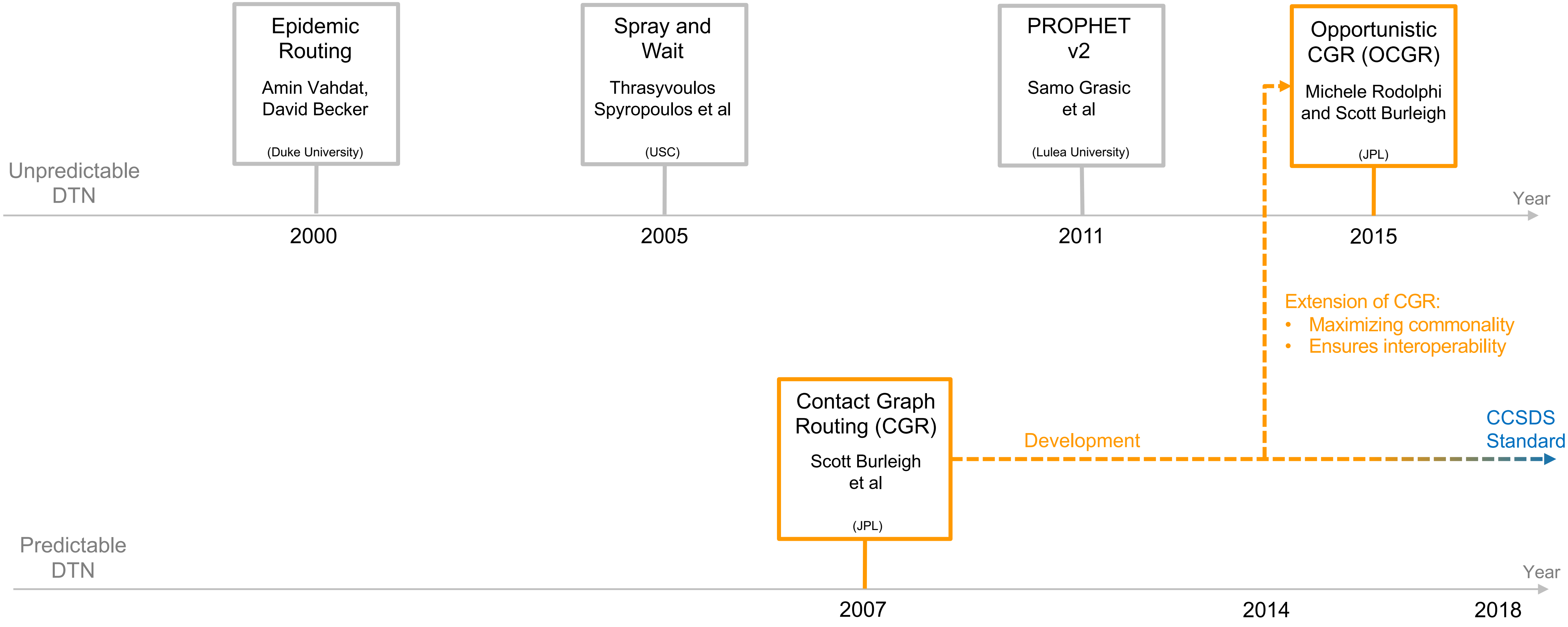
- Nodes with predictable contacts. Use DTN's CGR.
- Nodes with unpredictable contacts.

  2. Current Task: Compare performance CGR enhancement against specialized routing algorithms for networks of unpredictable contacts.

Research Approach

- **Step 1**: Define problem inputs.
  - Identify candidate routing algorithms to test.
  - Select motion for network nodes.
  - Define network configurations to study (e.g. number of nodes, transmission range).
- **Step 2**: Define network figures of merit.
  - Performance: Probability of delivering a bundle to destination.
  - Cost (not in $): Overhead ratio.
- **Step 3**: Prepare simulation testbed.
- **Step 4**: Run simulations and analyze results.
  - Measure network performance metrics over several hours as a function of the mobility model and network configuration.
- **(Future) Step 5**: Consider interactions with other parts/properties of the network (e.g. security, quality of service, etc.)

Routing Alternatives



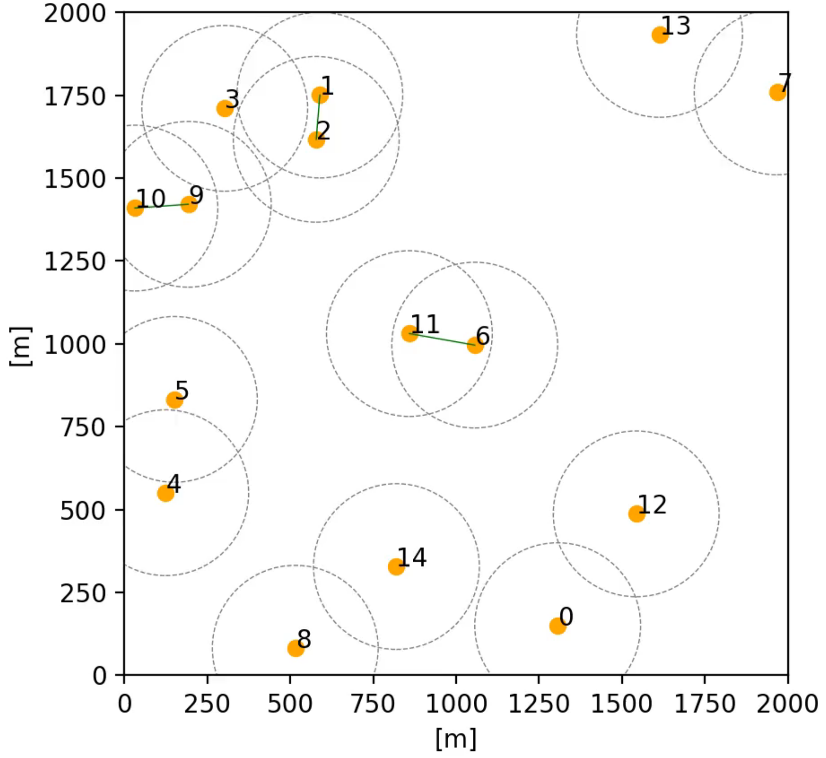
Opportunistic Contact Graph Routing

- Nodes have a contact history that stores contacts observed in the past with peer nodes.
- When two nodes meet, they exchange contact histories. This allows them to (hopefully) build a historical view of the network topology.
- Using this contact history, nodes predict contacts between themselves and their peers for a certain time horizon.
- Predicted contacts have associated a confidence level, number between 0 and 1 to indicate how certain a node is about this contact actually happening.
- When a bundle needs to be routed, the CGR procedure uses the union between the traditional contact plan and the set of predicted contacts to determine the next hop. This enables routing in both a scheduled and opportunistic DTN.
- Since there is no certainty that the bundle will arrive following this route, the sending node will keep sending the bundle through different routes until it is confident enough about delivery to destination.
- OCGR is configured using two parameters:
    - A route can only be selected for a bundle if it increase the delivery confidence by more than MIN_CONFIDENCE_IMPROVEMENT.
    - A node will keep sending copies of a bundle until it is MIN_NET_DELIVERY_CONFIDENCE confident of its delivery.

Description of Mobility Models

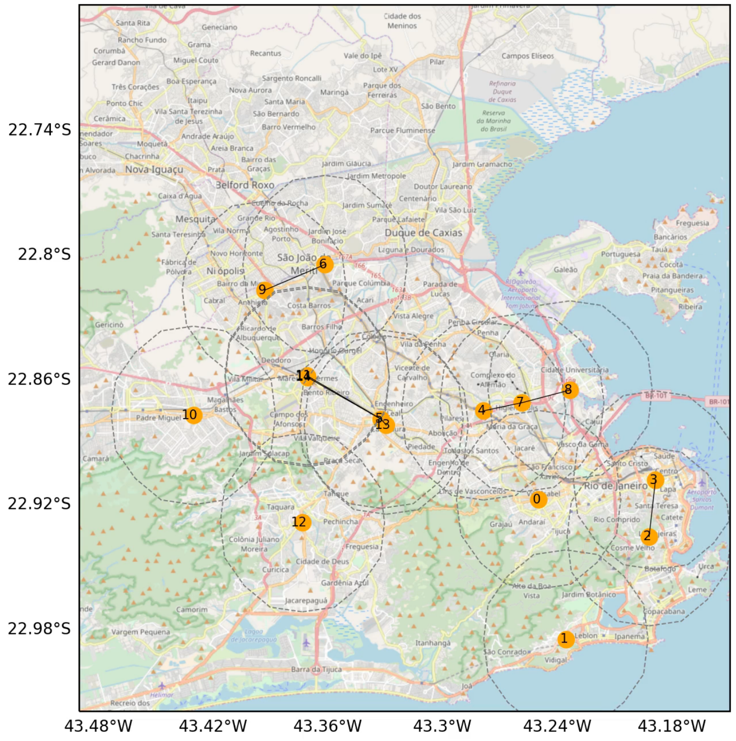
Random Waypoint Model

- Each node (orange dot) follows simulated fully random aperiodic motion.
- Nodes walk from target to target (not shown in movie).
- When two nodes are close enough, they establish a communication link.
- Applicable to people in museum, rovers heading to scientific targets.



Bus Motion

- Each node (bus in real-life) follows a non-deterministic periodic motion.
- Buses move in closed loops according to their route and traffic conditions.
- When two buses are close enough, they establish a communication link.
- Applicable to data mule between scientific locations.

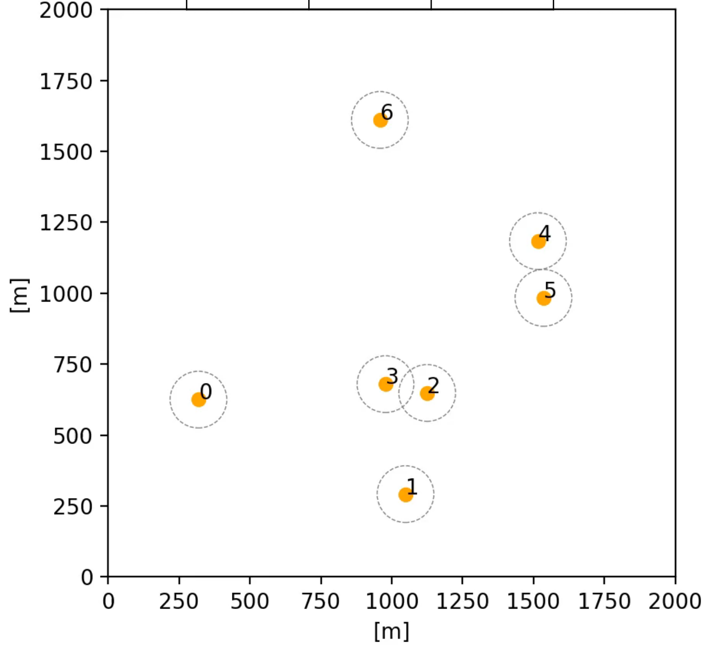


Description of Network Configurations

- The network configuration is given by three parameters:
  - Network sparsity (NS): Measures, at any point in time, how many neighbors are within transmission range.
  - Network dynamicity (ND): Measures the rate at which new connections are established in the system.
  - Network stability (NB): Measures how long a connection lasts once established

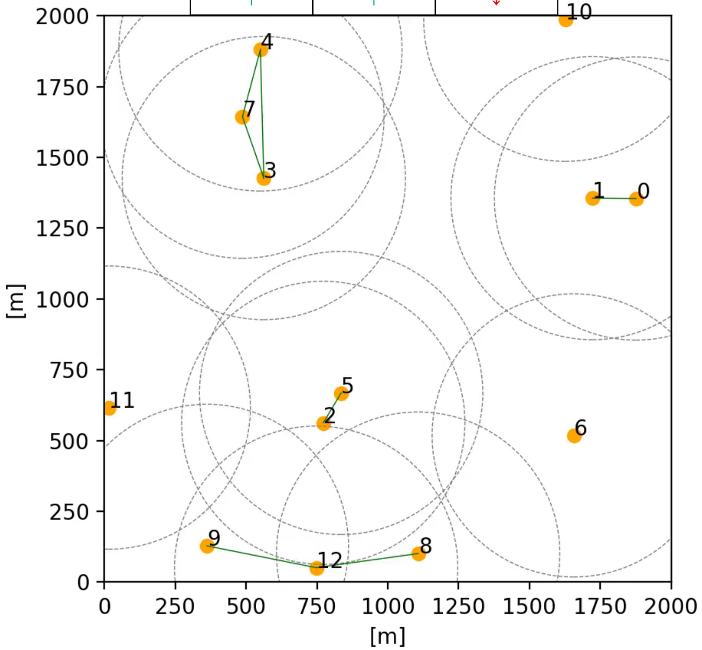
Sparsely Connected Network

NS	ND	NB
↓↓	↓↓	↓↓



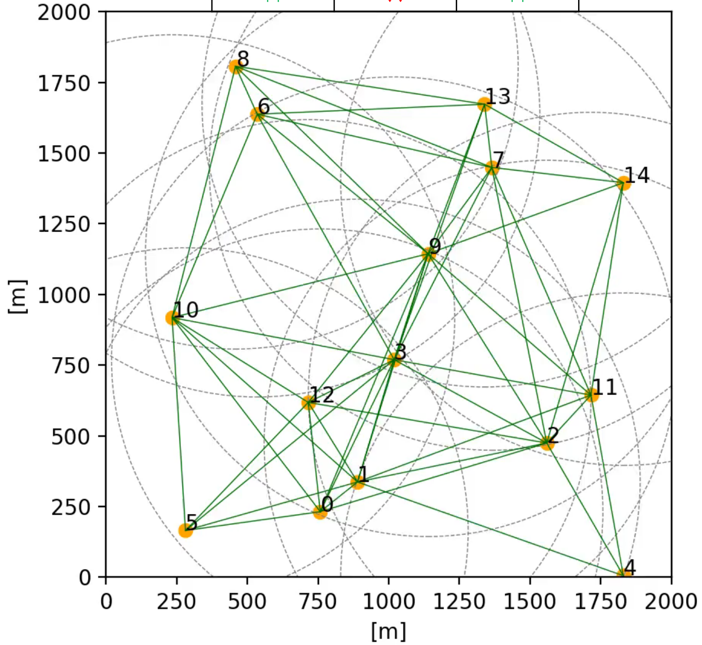
Medium Connected Network

NS	ND	NB
↑	↑	↓



Densely Connected Network

NS	ND	NB
↑↑	↓↓	↑↑



Random Waypoint Mobility Characterization

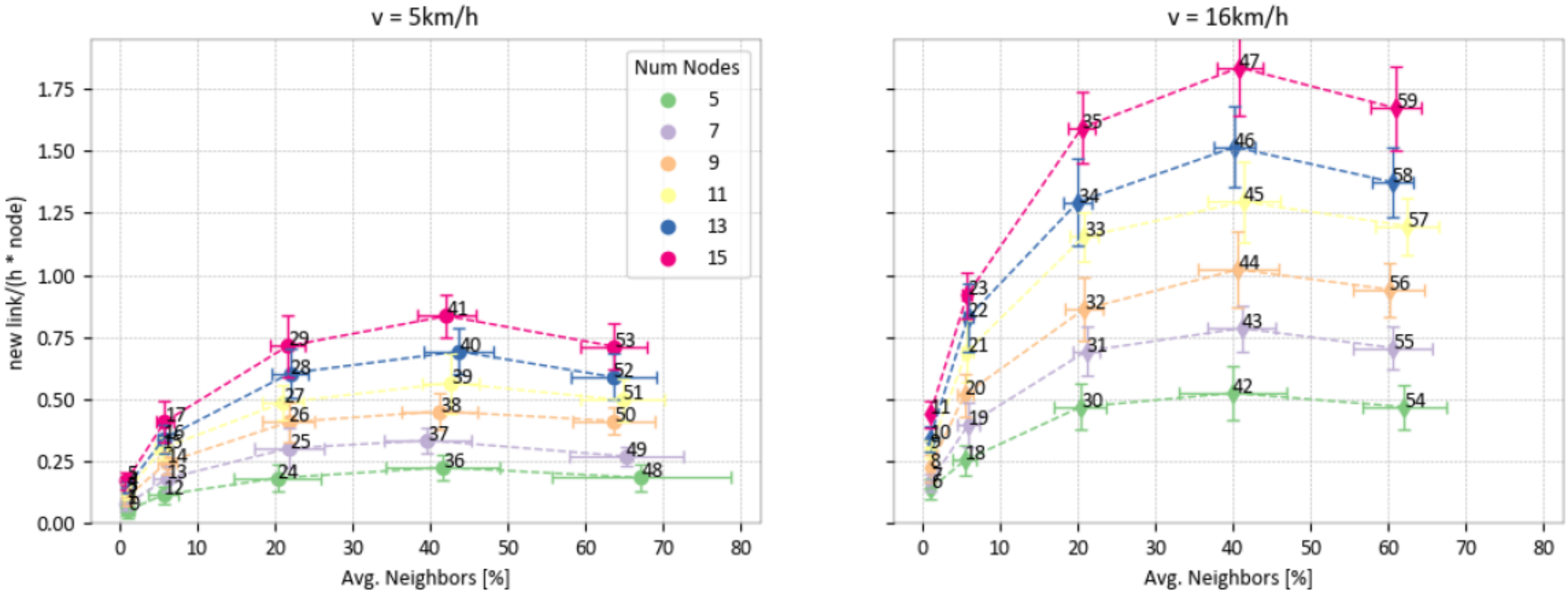


Fig. 1. Network Dynamicity vs. Sparsity

Simulation Inputs

- Simulation constants:
  - Node movement model: 2-way waypoint (**random aperiodic movement**).
  - Message size = 1MB
  - Message interval = 5 to 20 seconds, uniform distribution
  - Map size: 2000m x 2000m square.
  - Simulation duration: 2.5 hours
  - Number of simulations per scenario: 20 (traffic and movement are is random)
  - Buffer and TTL constraints: Unlimited in both cases.
  - Maximum OCGR contact history span: 30 minutes.
  - Transmission rate: 1Mbps (normalized rho $\rho \approx 0.2$ for nodes)

- A total of 60 network configurations were evaluated based on four criteria:
  - **Node Mobility**: Low ($v = 5km/h$, walking pace) vs. Medium ($v = 16km/h$, slow driving conditions).
  - **Node Density**: 5, 7, 9, 11, 13 and 15 users (max. expected number of users in DTN region).
  - **Transmission range**: 100m, 250m, 500m, 750m, 1000m.

Evaluation Metrics

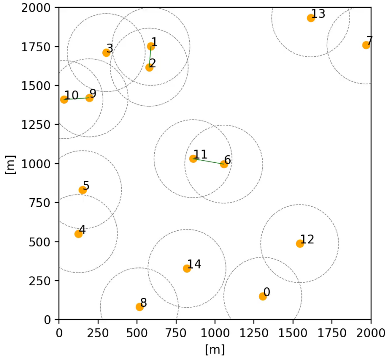
- Delivery Probability (PERFORMANCE):
    - Definition: Probability that a message is successfully delivered to its intended destination at least once prior to the end of the simulation.
    - Remark: A delivery probability of 1.0 is never achievable since bundles created just prior to the end of simulation will not be delivered.
    - Implementation: $\text{Delivery probability} = \frac{\text{\# bundles created}}{\text{\# bundles delivered}}$

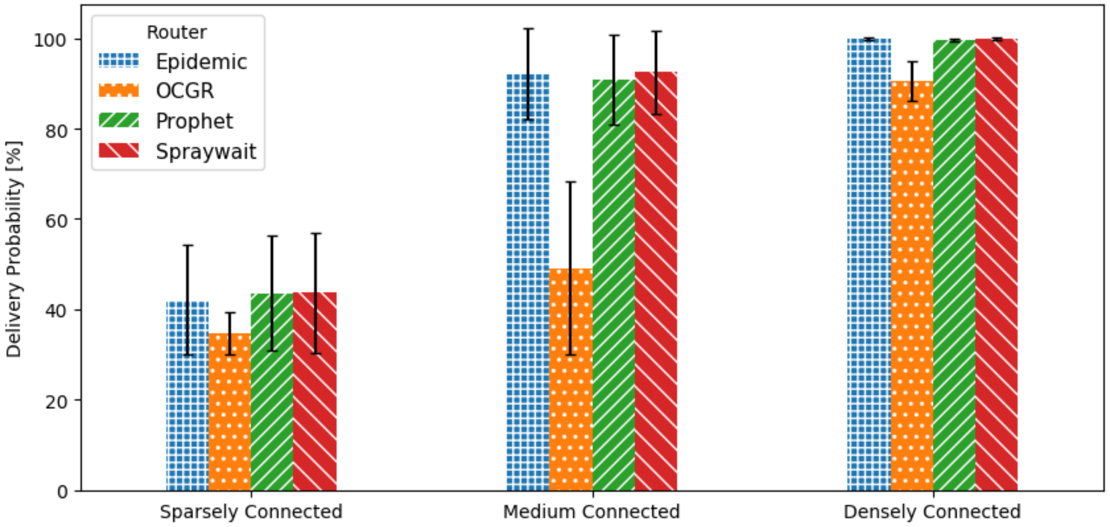
- Overhead Ratio (COST):
    - Definition: Ratio of bundles relayed to bundles delivered to destination
    - Remark: The minimum value for the overhead ratio is 0.0, achievable if all nodes can deliver a message directly to destination.
    - Implementation: $\text{Overhead ratio} = \frac{\text{\# bundles relayed} - \text{Number of bundles delivered}}{\text{\# bundles delivered}} = \frac{\text{\# relayed}}{\text{\# delivered}} - 1$

Analysis of Results: Delivery Probability

Random Waypoint Model

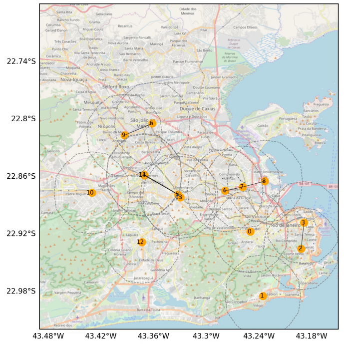
- Fully random aperiodic motion.
- Motion is simulated in computer.
- Applicable to rovers going from scientific target to scientific target.

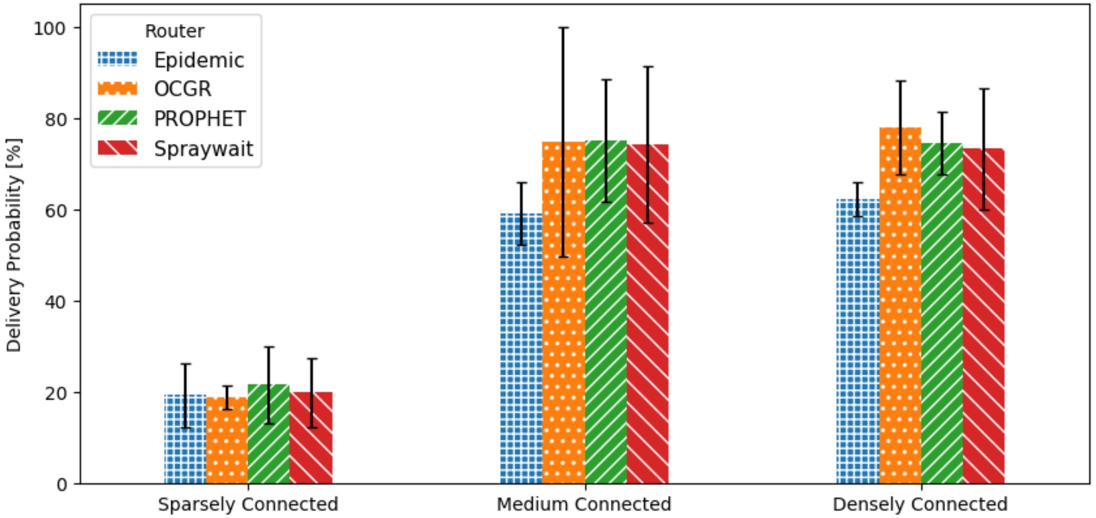




Bus Motion

- Non-deterministic periodic motion.
- Based on real-life GPS location of buses.
- Applicable to data mule going back and forth between scientific locations.





Analysis of Results – Overhead Ratio

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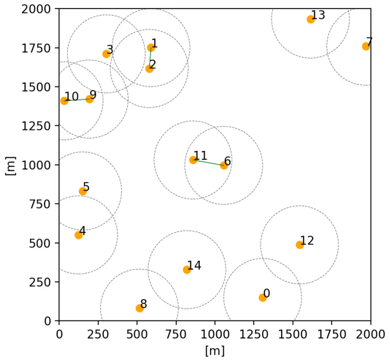

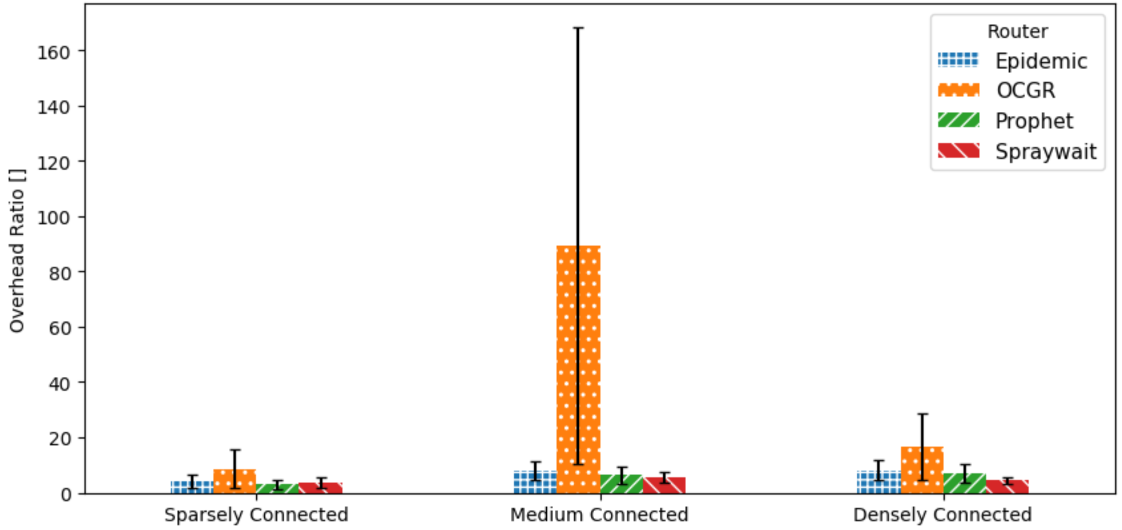

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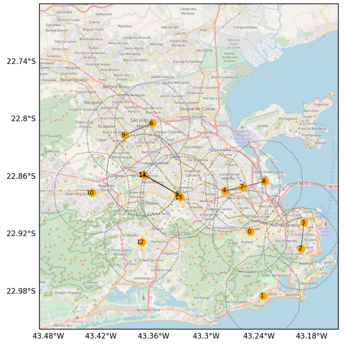
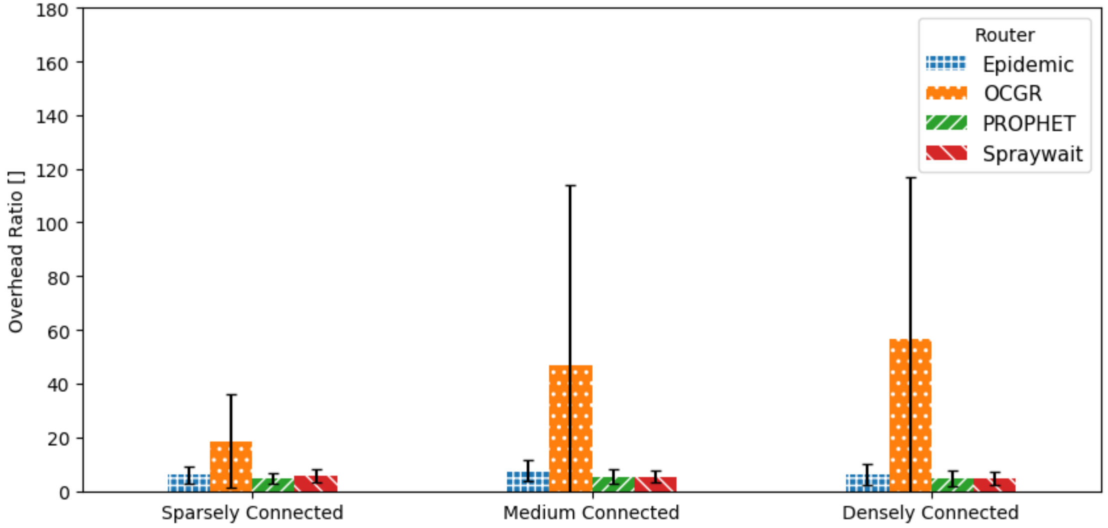




Summary and Future Work

- Lessons Learned:
  - The performance of OCGR greatly depends on the mobility model assumed and the type of network:
    - Since OCGR tries to predict future contacts, less variability in node motion results in better performance.
    - The current limitations of OCGR are especially notorious in medium connected networks (lots of links being created, lots of neighbors) since routing decisions are more unstable
  - The overhead ratio of OCGR tends to be higher than competing algorithms, especially for the random waypoint mobility model. This is due to several factors:
    - If the route prediction algorithm in OCGR is lost, then next hop for packets is essentially chosen at random.
    - All other algorithm have an initial setup phase were nodes exchange information about which packets they hold in memory. This is currently not present in OCGR.
    - All other algorithms have explicit ways to limit the number of times a packet is relayed. This helps network managers control flooding.
- Future Work:
  - Inherit elements from other opportunistic routing algorithms (e.g. exchange of data when contact start, explicit network control).
  - Modularize parts of OCGR (e.g. contact prediction algorithm) so that users could tailor router to specific network conditions.

Back-up Slides

Other Applications Enabled by Opportunistic DTNs

- Related to space:
  - Unconstrained mobility of surface assets on the Moon or Mars (e.g. opportunistic data mule between science areas).
  - Unconstrained mobility in highly irregular terrains (e.g. Moon cave or crater edges).
  - Distributed on-board computing across rovers on the surface of Mars (see MOSAIC R&TD).
  - Rapid repointing of agile satellite constellation due to unexpected events (e.g. fire, flash-flood).

- Not related to space:
  - Exploration of areas without infrastructure (e.g. reindeer herd tracking in Norway/Sweden).
  - Real-time information exchange in vehicular networks.

Opportunistic Routing Alternatives

DTN Subcategory	Routing Protocol	Message Replication Mechanism	Replication Limit	Residual Delivery Mechanism	Contact Probability Estimation	Router Prediction	Router Parameters
Discovered contacts	Epidemic	Any encounter	Message hop count	-	-	-	1) Max. number of hops (H): Bundles that are relayed more than H are dropped
	Spray&Wait	Binary tree	Number of messages replicated	Direct delivery to destination	-	-	1) Max. number of bundle copies (L): During the spray phase, at most L copies will be generated
Predictable contacts	PROPHET	Any encounter	Message hop count	-	1) Update delivery probability 2) Age delivery probability 3) Exchange if delivery probability is better	Probability of node A delivering bundles to node B	1) Max probability of encountering any node (P_{max}). 2) Probability aging constant (γ). 3) Scaling constant that decides the strength of the delivery probability transitivity (β). 4) Typical/Average time delta between contacts (I_{typ}).
	OCGR	As dictated by CGR with predicted contacts	Message time-to-live	-	1) Update delivery confidence 2) Compute route using CGR 3) Exchange if delivery confidence is increased	Sequence of contacts (up to the prediction horizon), including contact duration, rate and gap. Each contact is assigned a confidence that is then used to compute the bundle delivery probability through a route.	1) High base confidence (HBC): Assigned as initial confidence for a predicted contact if $\sigma_{duration} < \mu_{duration}$ and $\sigma_{gaps} < \mu_{gaps}$ for contact history. 2) Low base confidence (LBC): Assigned as initial confidence for a predicted contact if $\sigma_{duration} > \mu_{duration}$ and $\sigma_{gaps} > \mu_{gaps}$ for contact history. 3) Prediction horizon = current time + span of contact history 4) Gap, rate and duration properties of predicted constant are constant and equal to the mean estimated from the contact history. 5) Min confidence improvement (MCI): If $\frac{new\ delivery\ confidence}{old\ deliver\ confidence} \geq MCI$, then forward bundle through this route. It is only applicable to non critical bundles. 6) Min net delivery confidence $(MNDC)$: If a bundle's delivery confidence < MNDC, send and add to limbo again for another round of re-routing.

Random Waypoint Mobility Characterization

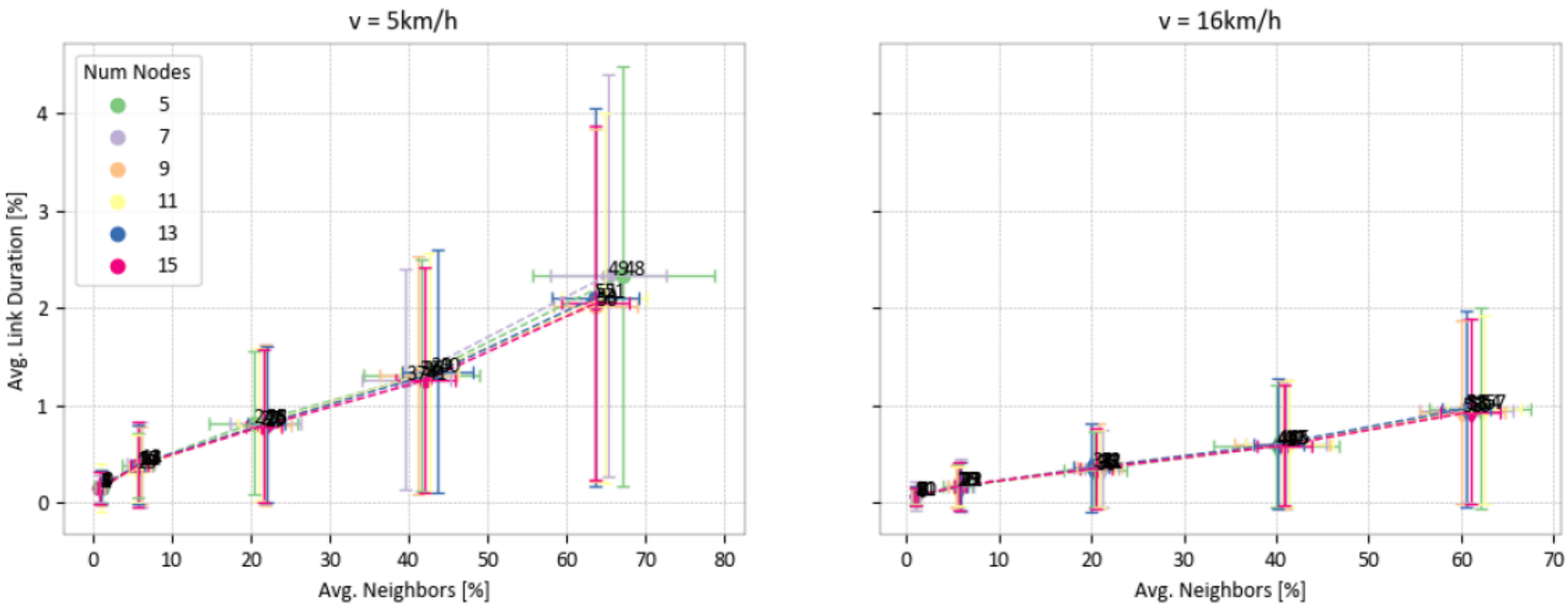


Fig. 2. Network Stability vs. Sparsity

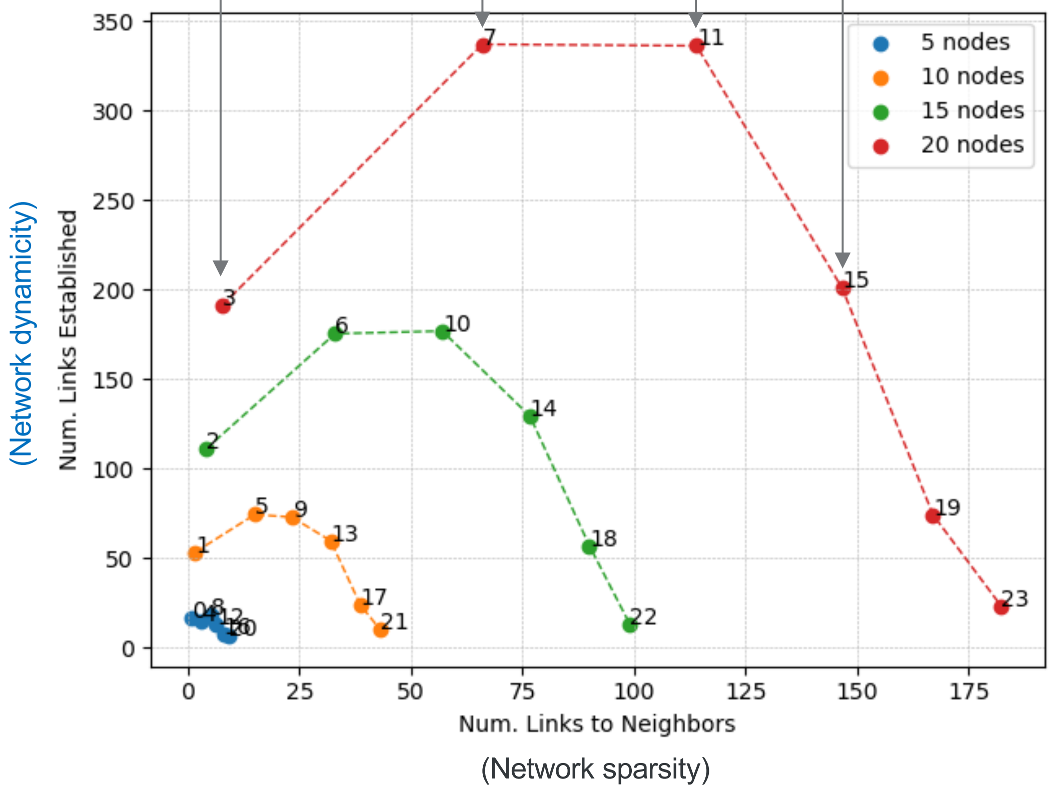
Bus Mobility Characterization

ID 3
- 20 buses
- **2.5km tx. range**

ID 7
- 20 buses
- **10km tx. range**

ID 11
- 20 buses
- **15km tx. range**

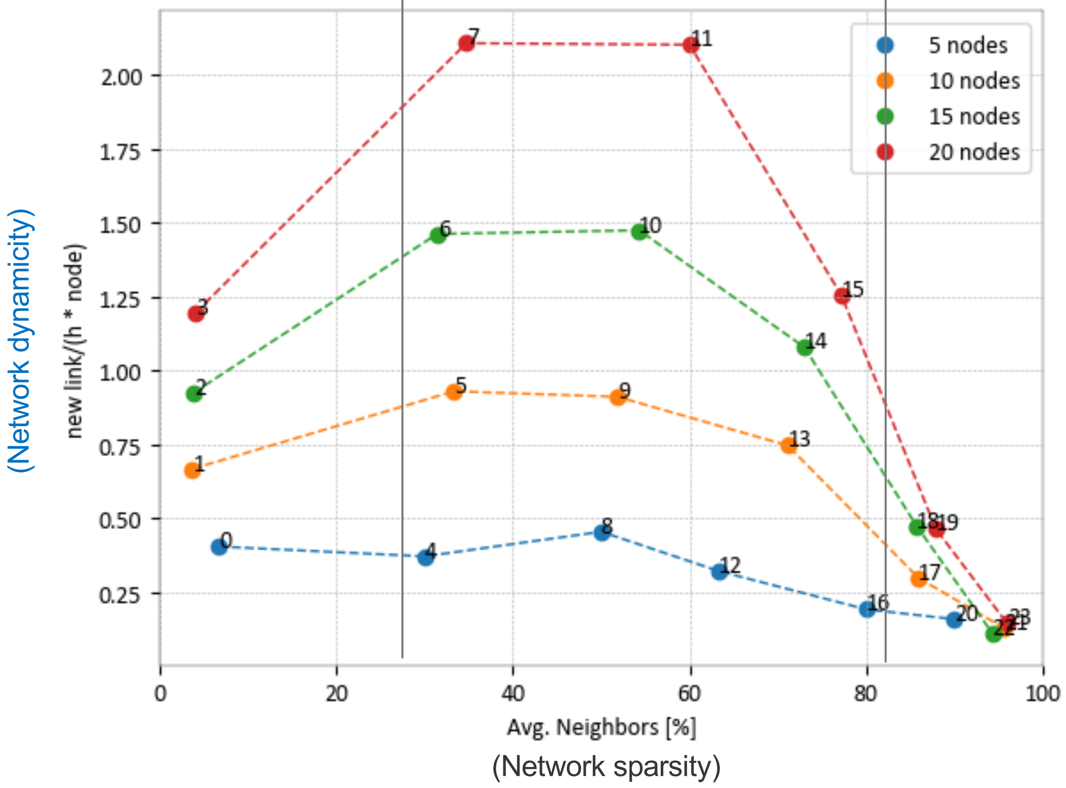
ID 15
- 20 buses
- **20km tx. range**



Sparse Network
- Scattered nodes.
- Contact opportunities are rare.

Connected Network
- Intermediate case between spare and dense network.
- Rate of new contacts is maximized.

Dense Network
- Nodes can see each other most of the time.
- Contacts are very long, so rate of new contacts is low.



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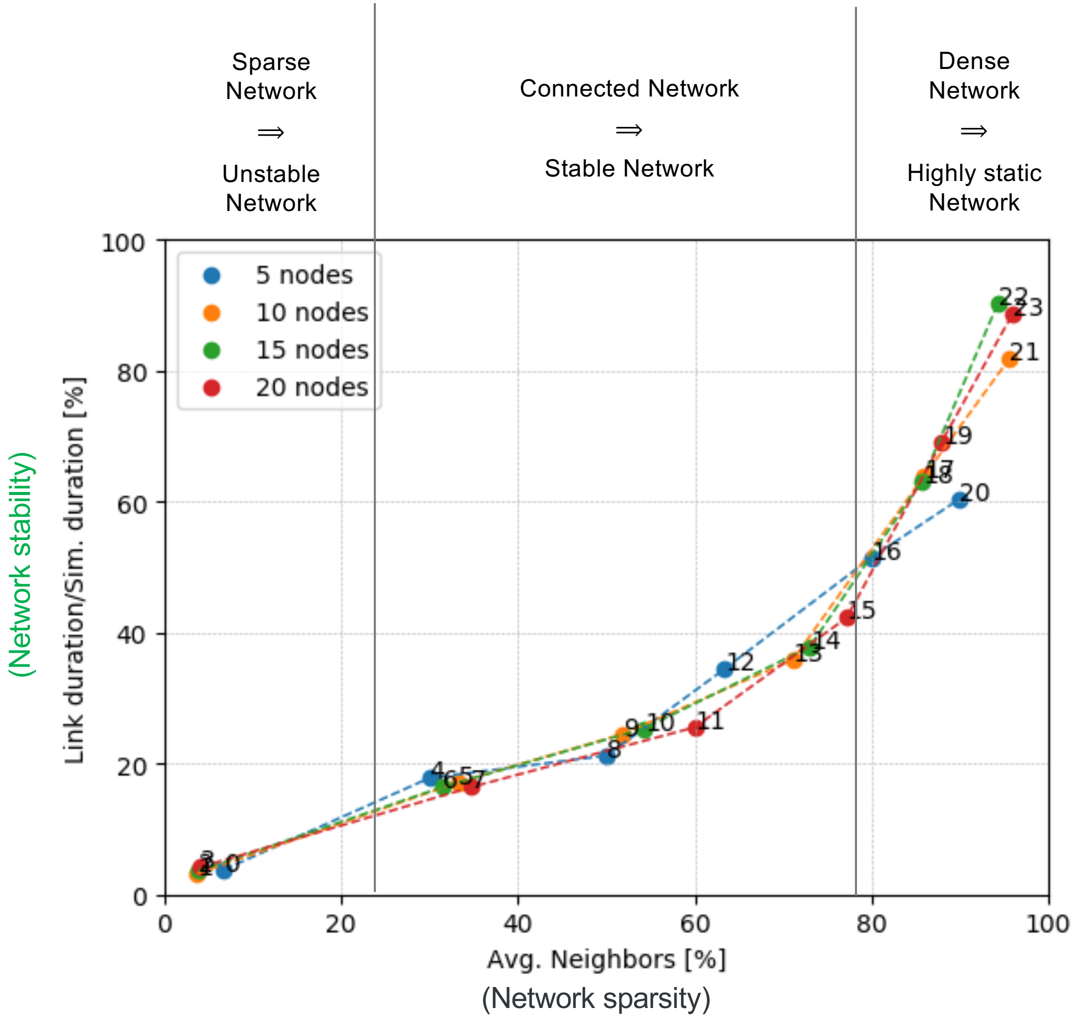

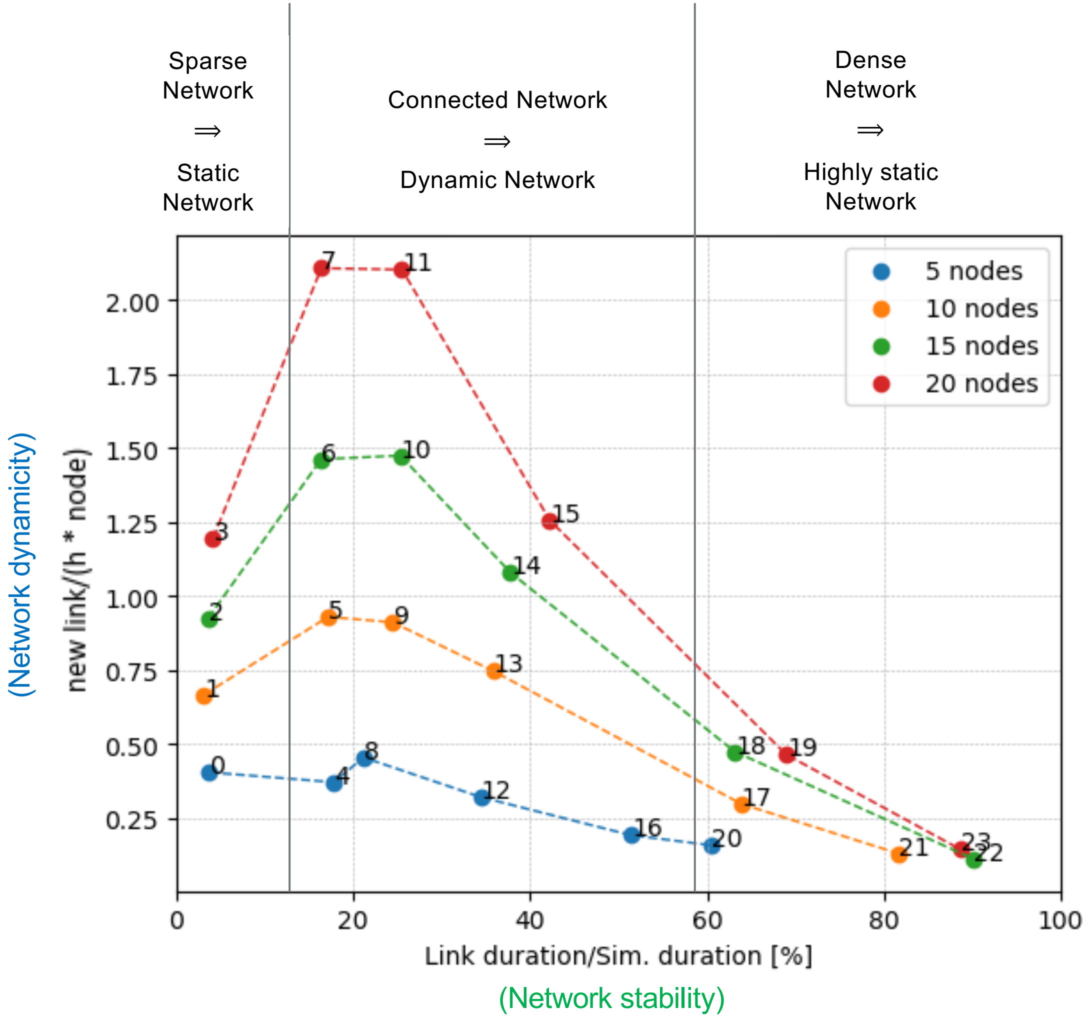

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